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Renewable energy potential assessment in Jordan

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ABSTRACT

This paper is directed to assess the potential of renewable energy resources, wind and solar, in Jordan. Long-term measured data of wind speed and solar insolation levels at different locations in the country are used in this study. Statistical and metrological approaches are utilized to obtain the characteristics of both wind speed and solar irradiance. The power potential of the two resources is also evaluated. The results obtained show that Jordan has a great potential of wind and solar in various locations. Therefore, projects deal with practical implementation of wind and solar resources in the country are highly recommended.

Contents

1. Introduction

The rate of energy consumption in Jordan is rising rapidly and oil is the dominant energy sector for economic and social developments. Since Jordan is an oil importing country, high amount of the national hard currency is spent to import crude oil. For example, in year 2004 the country spent about 1.65 million US$ on importing and refining petroleum products [1]. It is expected that the importance of this economical issue and the environmental pollution problem, associated with the use of conventional energy sources, will motivate both universities and industry in Jordan to impose a great focus on the utilization of wind and solar energy resources.

In the literature there is a lot of research work dealing with the use of renewable energy resources in different locations in the world. Omer [2] investigated the use of wind energy to drive water pumps in many places in Sudan. Bekele and Palm [3] have investigated wind energy potential at four locations in Ethiopia and they found that three of them have an acceptable wind speed level. Wind speed characteristic and wind power potential in seventeen locations in Tunisia are studied in [4]. The research work presented in [5] is directed to evaluate the energy and the environmental performances of electricity produced by wind energy in Italy. The study in [6] concentrated on some aspects of using wind energy in Brazil. Shaahid and El-Amin [7] investigated the techno-economic aspect in using hybrid PV-diesel-battery power system to supply the load demand in a remote village in Saudi Arabia. The authors in [8] analyzed solar irradiation data to evaluate the possibility of utilizing hybrid PV-diesel-battery power system to supply a typical residential load in Dhahran-Saudi Arabia. In publication [9] Badran introduced a survey for the use of wind energy in Jordan to drive water pumps; even directly through mechanical means or indirectly through wind-driven electric generator. The authors in [1] applied two approaches to evaluate space-heating system in Jordan, and they showed that wind energy as well as solar energy is the most favorable options for space heating application. Tarawneh and Sahin in [10] have applied a method to compute the average wind speed in some places in Jordan.

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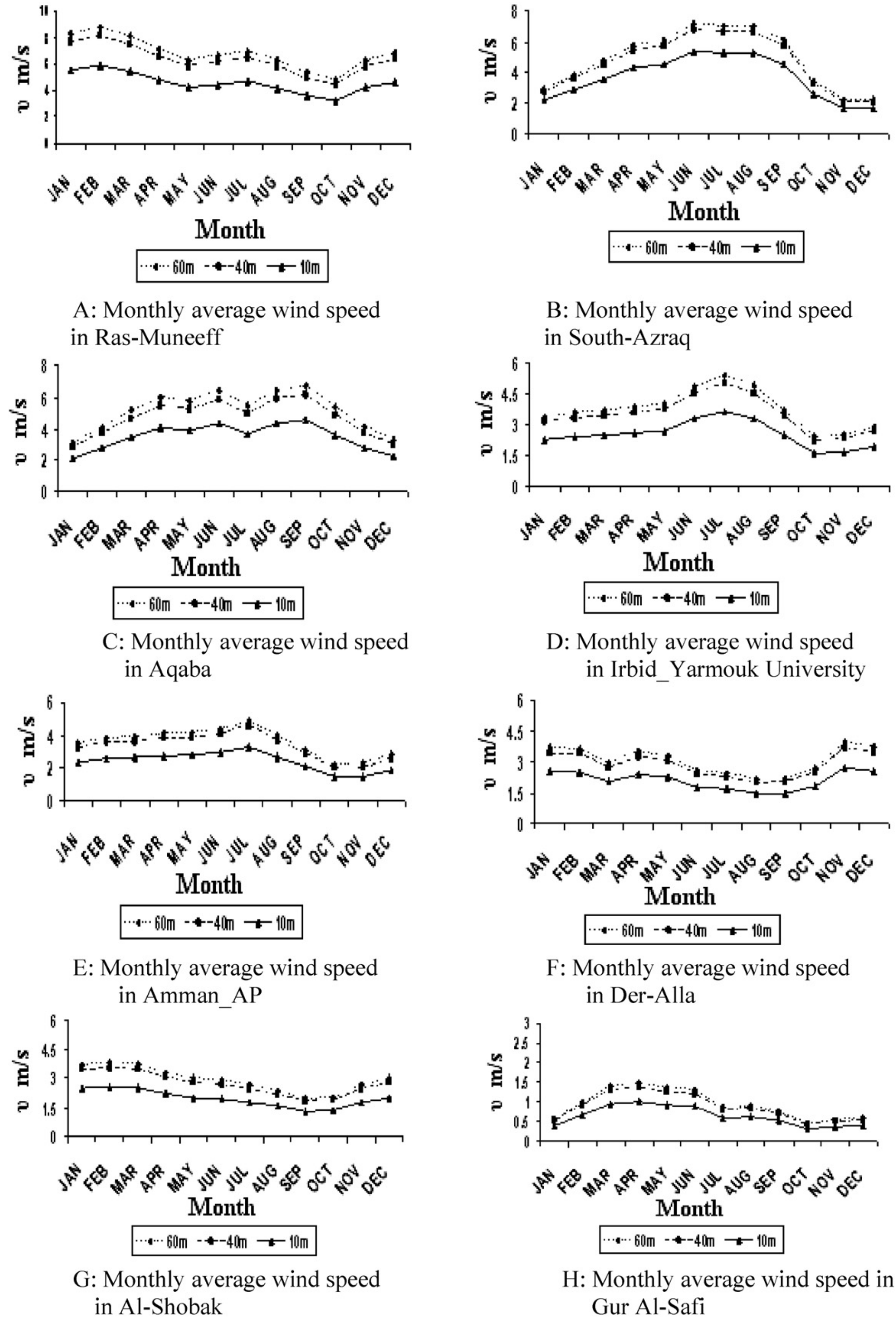


Fig. 1. (A) Monthly average wind speed in Ras-Muneeff. (B) Monthly average wind speed in South-Azraq. (C) Monthly average wind speed in Aqaba. (D) Monthly average wind speed in Irbid_Yarmouk University. (E) Monthly average wind speed in Amman_AP. (F) Monthly average wind speed in Deir-Alla. (G) Monthly average wind speed in Al-Shobak. (H) Monthly average wind speed in Gur Al-Safi.

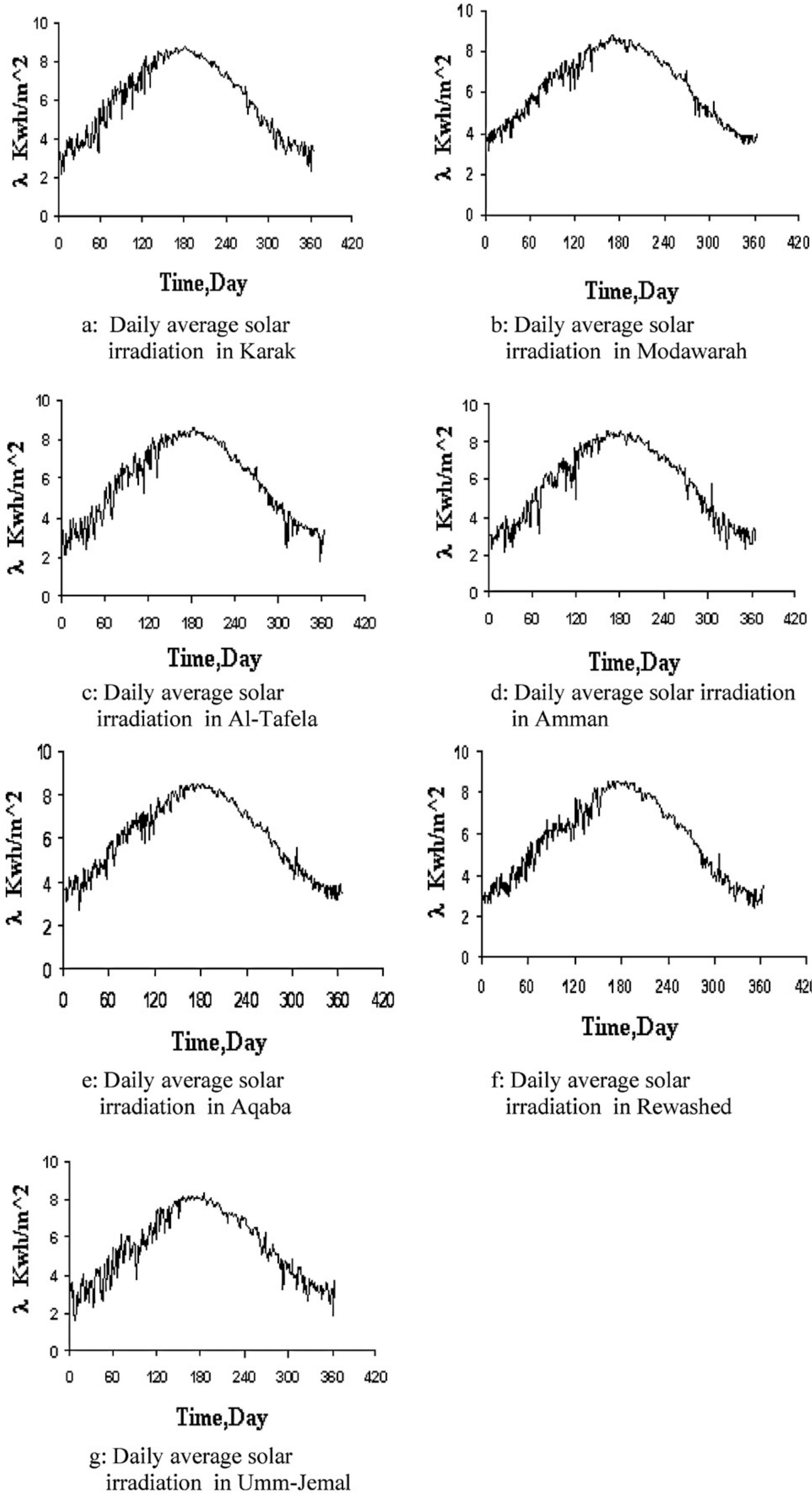


Fig. 2. (A) Daily average solar irradiation in Karak. (B) Daily average solar irradiation in Modawarah. (C) Daily average solar irradiation in Al-Tafela. (D) Daily average solar irradiation in Amman. (E) Daily average solar irradiation in Aqaba. (F) Daily average solar irradiation in Rewashed. (G) Daily average solar irradiation in Umm-Jemal.

Nomenclature

V	classified wind speed
f	occurrence frequency
F	cumulated frequency
V_M	mean wind speed
V_E	most energetic wind speed
V_F	most frequent wind speed
h_r	reference height of WT
V_{hr}	the wind speed at reference height of WT
h	the desired height of WT
V_h	wind speed at the desired height of WT
z	roughness height
ρ	air density (1.225 kg/m^3)
λ	solar insolation
λ_M	mean solar insolation level
λ_F	most frequent solar insolation level
$f(V)$	the distribution probability of wind speed V
A	Weibull scale parameter
K	the dimensionless Weibull shape parameter
Γ	the gamma function
$f(\lambda)$	the distribution probability of the solar irradiance

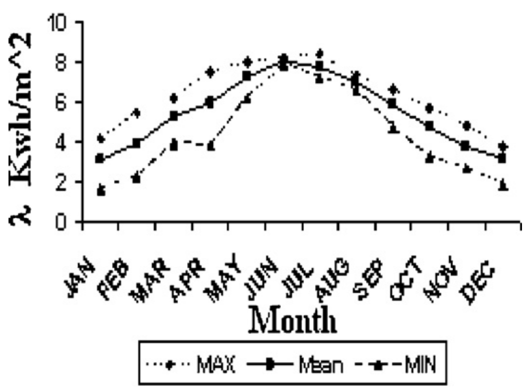
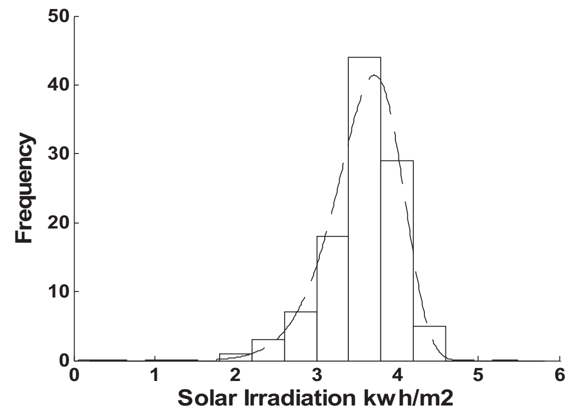


Fig. 3. Monthly average, max, min solar irradiation in Umm-Jemal.

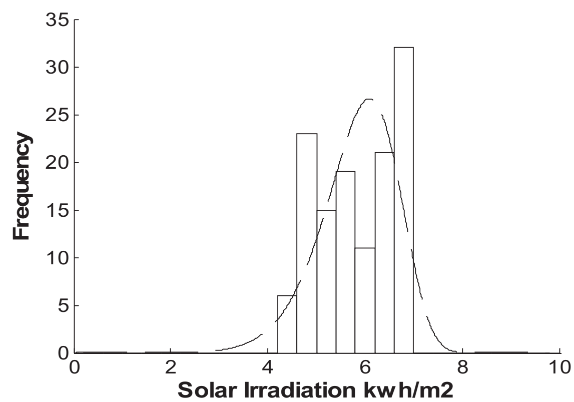
The research work presented in this paper is aimed to investigate the potential of wind and solar energy resources in Jordan. Long period measured data of wind speed and solar irradiation, provided by Meteorological Department and National Energy Research Center, for different sites in Jordan are used. Wind speed characteristics, wind power, and wind energy in each chosen site are all evaluated using both meteorological and statistical approaches. The two methods are also used to estimate the behavior of solar irradiance, solar power and solar energy at each selected location.

Table 1
selected stations to evaluate wind energy potential in Jordan.

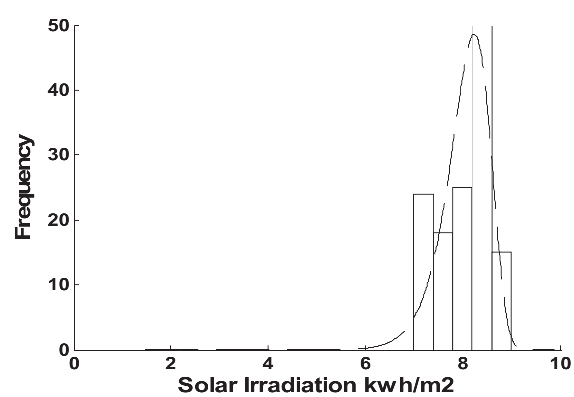
Site	Latitude (°N)	Longitude (°E)	Elevation (m)
Aqaba	29′33′	35′00′	51
Deir-Alla	32′13′	35′37′	−224
Ghor Al-Safi	31′02′	35′28′	−350
Ras-Muneef	32′21′	35′45′	1150
Amman_AP	31′58′	35′58′	772
Irbid_YU	31′98′	35′51′	616
Shoubak	30′31′	35′53′	1365
South-Azraq	31′49′	36′49′	521



I: Histogram and PDF for cluster A in Karak



II: Histogram and PDF for cluster B in Karak

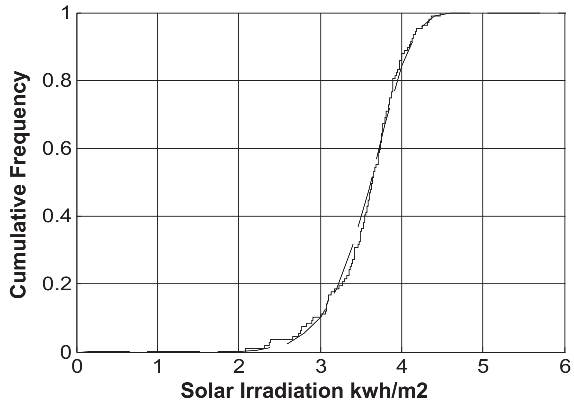


III: Histogram and PDF for cluster C in Karak

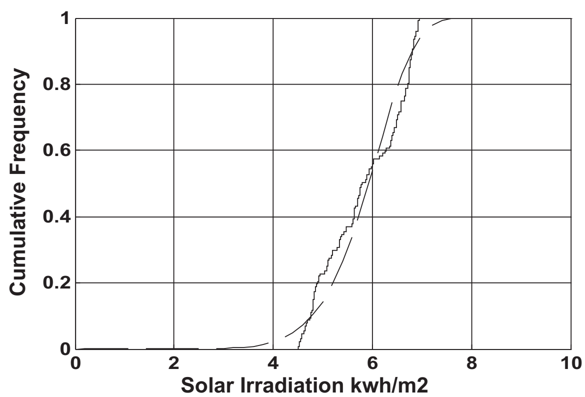
Fig. 4. (A) Histogram and PDF for cluster A in Karak. (B) Histogram and PDF for cluster B in Karak. (C) Histogram and PDF for cluster C in Karak.

2. Analysis

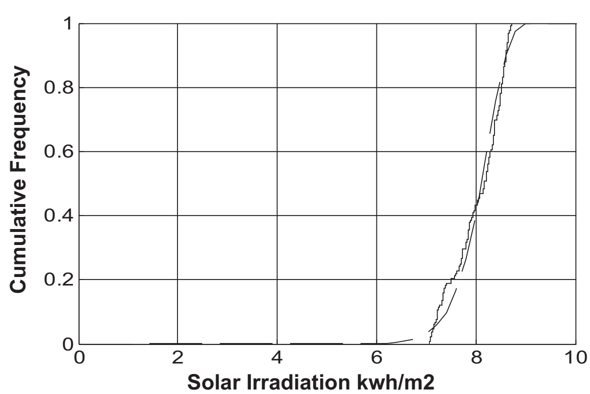
Based on the long term gathered meteorological data; wind speeds and irradiance levels, the potential of wind and solar energy resources can be evaluated using different approaches. Meteorological and statistical approaches are usually utilized for this purpose. In the following sub-sections, these two approaches including the mathematical representation are presented.



A: Plot of the empirical and fitted distribution for cluster A in Karak



B: Plot of the empirical and fitted distribution for cluster B in Karak



C: Plot of the empirical and fitted distribution for cluster C in Karak

Fig. 5. (A) Plot of the empirical and fitted distribution for cluster A in Karak. (B) Plot of the empirical and fitted distribution for cluster B in Karak. (C) Plot of the empirical and fitted distribution for cluster C in Karak.

2.1. Meteorological approach

Based on long-period collected meteorology wind speed data, the occurrence frequencies of wind speed are defined by the following equation [4]:

$$f(V) = F(V+1) - F(V) \tag{1}$$

Wind speed characteristics can be mathematically expressed by [2,4]:

$$V_M = \sum_{i=0}^{n} V_i f(V_i) \tag{2}$$

$$V_E = V(E(V)\max i) \tag{3}$$

$$V_F = V(f(V)\max i) \tag{4}$$

In the present work, wind speeds are measured at a height hr of 10 m. The hub height h of the desired wind turbine may differs from the reference height, for example $h = 40$ m. Therefore, wind speeds at an elevation of h have to be normalized using the following formula [2]:

$$\frac{V_h}{V_{hr}} = \frac{\ln(h/z)}{\ln(hr/z)} \tag{5}$$

Using the Betz formula, the recoverable wind power per unit area could be given by:

$$P_W = \frac{116}{227}\rho(1+3z^2)\sum_{i=1}^{n} V_i^{3} f(V_i) \tag{6}$$

The annual wind energy per unit area, in kW/m^2/Y, could be computed using the following equation [2,11]:

$$E_W = \frac{24 \times 365}{1000} P_W \tag{7}$$

Using the recorded tables for the meteorology solar insolation levels, the occurrence frequency of solar irradiance and the characteristics of solar irradiance could be defined by the following expression [12,13]:

$$f(\lambda) = F(\lambda+1) - F(\lambda) \tag{8}$$

$$\lambda_M = \sum_{i=0}^{n} \lambda_i f(\lambda_i) \tag{9}$$

$$\lambda_F = \lambda(f(\lambda)\max i) \tag{10}$$

2.2. Statistical methods

Weibull distribution (WD) method is the most used statistical approach to represent the distribution of wind speeds and that of solar irradiance [4,12,13]. This is due to its greater flexibility and simplicity, compared with other methods. In addition, it can give a good fit to experimental data. The probability density function of the wind speed is given by [4]:

$$f(V) = \frac{K}{A}\left(\frac{V}{A}\right)^{K-1} \exp\left[-\left(\frac{V}{A}\right)^{K}\right] \tag{11}$$

The cumulative distribution function of the wind speed is given by:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{A}\right)^{K}\right] \tag{12}$$

Wind speed characteristics and the variance of Weibull distribution $V_{ar}(V)$ are defined by the following equations [2,4]:

$$V_M = A\Gamma\left(1+\frac{1}{K}\right) \tag{13}$$

$$V_E = A\left(1+\frac{2}{K}\right)^{1/K} \tag{14}$$

$$V_F = A\left(1-\frac{1}{K}\right)^{1/K} \tag{15}$$

Table 2
Wind speed characteristics, wind power and wind energy computed at a height of 10 m.

Location	Method	V_M	V_F	V_E	RMSE	*P*-value	C.S.	P_W	E_W
Aqaba	**W**: $A=3.7900$, $K=4.2373$	3.447	3.557	4.152	0.243	0.773	0.053	34.74	304.32
	M	3.440	3.180	4.340				37.30	326.75
Deir-Alla	**W**: $A=2.3414$, $K=3.5274$	2.108	2.130	2.659	0.258	0.465	0.117	8.51	74.56
	M	2.112	1.689	2.732				8.99	78.75
Gur Al-Safi	**W**: $A=0.6658$, $K=1.4729$	0.602	0.308	1.192	0.059	0.301	0.013	0.19	1.65
	M	0.616	0.350	1.100				0.48	4.19
Ras-Muneef	**W**: $A=4.9779$, $K=4.3738$	4.535	4.691	5.425	0.595	0.093	0.171	80.45	704.78
	M	4.549	4.418	6.418				82.96	726.73
Amman_AP	**W**: $A=2.7203$, $K=3.4215$	2.445	2.459	3.112	0.044	0.726	0.002	13.83	121.11
	M	2.442	2.535	3.115				13.59	119.08
Irbid_YU	**W**: $A=2.7814$, $K=3.6726$	2.509	2.551	3.131	0.089	0.819	0.008	14.50	127.01
	M	2.504	2.656	3.244				15.44	135.29
Shoubak	**W**: $A=2.1932$, $K=3.3869$	1.970	1.978	2.515	0.257	0.406	0.103	7.27	63.67
	M	1.976	1.672	2.193				7.06	61.87
South-Azraq	**W**: $A=4.1036$, $K=2.6257$	3.646	3.419	5.091	0.616	0.156	0.253	47.63	417.20
	M	3.639	4.456	5.344				46.57	407.97

Table 3
Wind speed characteristics, wind power and wind energy computed at a height of 40 m.

Location	Method	V_M	V_F	V_E	RMS	*P*-value	C.S.	P_W	E_W
Aqaba	**W**: $A=5.1331$, $K=4.2373$	4.668	4.817	5.626	0.237	0.773	0.038	86.31	756.06
	M	4.659	4.410	5.570				90.07	788.98
Deir-Alla	**W**: $C=3.1711$, $K=3.5274$	2.854	2.885	3.405	0.307	0.465	0.119	21.14	185.23
	M	2.860	2.359	3.480				20.93	183.35
Gur Al-Safi	**W**: $A=0.9017$, $K=1.4729$	0.816	0.417	1.614	0.099	0.301	0.043	0.47	4.10
	M	0.834	0.560	1.520				1.13	9.89
Ras-Muneef	**W**: $A=6.8486$, $K=4.3739$	6.240	6.454	7.464	0.297	0.093	0.039	209.52	1835.37
	M	6.258	6.204	7.014				214.71	1880.83
Amman_AP	**W**: $A=3.7426$, $K=3.4214$	3.363	3.383	4.282	0.055	0.726	0.003	36.00	315.39
	M	3.359	3.463	4.333				33.58	294.15
Irbid_YU	**W**: $A=3.8266$, $K=3.6726$	3.452	3.509	4.308	0.086	0.819	0.006	37.75	330.72
	M	3.446	3.414	4.422				38.37	336.13
Shoubak	**W**: $A=3.0174$, $K=3.3870$	2.710	2.721	3.461	0.296	0.406	0.113	18.93	165.79
	M	2.715	2.242	3.278				18.72	164.01
South-Azraq	**W**: $A=5.1773$, $K=2.6257$	4.600	4.312	6.424	0.805	0.156	0.340	95.64	837.84
	M	4.591	5.666	6.754				94.40	826.94

$$\mathrm{Var}(V) = A^2\left[\Gamma\left(1+\frac{2}{K}\right) - \Gamma^2\left(1+\frac{1}{K}\right)\right] \tag{16}$$

For any reality x positive not null, Γ can be mathematically expressed by:

$$\Gamma(x) = \int_0^{+\infty} t^{x-1}e^{-t}dt \tag{17}$$

Based on Betz formula, the theoretical wind power per unit area, in W/m^2 could be given by:

$$P_W = \frac{116}{227}\rho(1+3z^2)A^3\,\Gamma\left(1+\frac{3}{K}\right) \tag{18}$$

Using WD method, the probability density function of the solar irradiance is given by:

$$f(\lambda) = \frac{K}{A}\left(\frac{\lambda}{A}\right)^{K-1}\exp\left[-\left(\frac{\lambda}{A}\right)^K\right] \tag{19}$$

The cumulative distribution function of the solar insolation could be given by:

$$F(\lambda) = 1-\exp\left[-\left(\frac{\lambda}{A}\right)^K\right] \tag{20}$$

The solar irradiance characteristics are defined by the following expressions:

$$\lambda_M = A\Gamma\left(1+\frac{1}{K}\right) \tag{21}$$

$$\lambda_F = A\left(1-\frac{1}{K}\right)^{1/K} \tag{22}$$

The output electrical power of a PV-generator depends on the random variation of the environmental parameters (irradiance and ambient temperature) and the non-linear *I–V* characteristic of the solar cell module constituting the generator. Detailed mathematical derivations concerning with PV model can be found in [13].

Table 4
Selected stations to evaluate solar energy potential in Jordan.

Station	Location	Latitude (°N)	Longitude (°E)	Elevation (m)
National Energy Research Center	Amman	32′01′	35′52′	1041
Rawdat Basma Municipality	Umm-Jemal	32′17′	36′21′	682
Rewashed Agriculture Dep.	Al Mafraq	32′30′	38′11′	684
Tafela University College	Al-Tafela	30′50′	35′38′	1259
Karak University College	Al Karak	31′09′	35′44′	976
Modawara Border point	Ma'an	29′12′	36′00′	355
Aqaba Water Company	Al Aqaba	29′32′	35′00′	37

Table 5
The results of solar irradiation characteristics and solar power potential.

Location	Cluster	Method	λ_M	λ_M	*P*-value	RMSE	C.S.	λ_{max}	λ_{min}	P_λ	E_λ
Karak	A	**W**: $C=3.7579$, $K=9.8287$	3.572	3.572	0.850	0.140	0.011			429.2	459.3
		M	3.717	3.706				4.944	2.077	429.3	459.3
	B	**W**: $C=6.1775$, $K=8.7538$	5.843	5.843	0.057	0.647	0.124			761.4	1112.1
		M	5.832	6.758				7.993	5.035	761.7	1112.5
	C	**W**: $C=8.2603$, $K=20.6515$	8.048	8.048	0.229	0.417	0.040			1102.3	1964.3
		M	8.037	8.637				8.712	8.019	1097	1954.8
Modawarah	A	**W**: $C=4.8816$, $K=6.9861$	4.566	4.775	0.068	0.535	0.1420			574.8	937
		M	4.572	4.019				5.995	3.151	575.3	937.8
	B	**W**: $C=7.0579$, $K=20.6094$	6.876	7.041	0.481	0.033	0.0003			921.2	1140
		M	6.875	7.087				7.497	6.007	919.1	1137.4
	C	**W**: $C=8.3522$, $K=30.858$	8.204	8.343	0.843	0.022	0.0002			1125	1608.8
		M	8.209	8.312				8.816	7.508	1123.3	1606.3
Tafela	A	**W**: $C=4.1439$, $K=5.1311$	3.811	3.973	0.115	0.549	0.189			464.4	780.2
		M	3.812	3.196				5.469	1.775	465.1	781.3
	B	**W**: $C=7.1112$, $K=10.5737$	6.781	7.045	0.079	0.414	0.053			903.6	1570
		M	6.788	6.460				7.996	5.507	906	1574.2
	C	**W**: $C=8.3179$, $K=61.8052$	8.242	8.316	0.118	0.147	0.005			1122.4	1052.8
		M	8.234	8.109				8.616	8.009	1127.2	1057.3
Aqaba	A	**W**: $C=4.0266$, $K=12.8497$	3.868	4.001	0.581	0.132	0.0090			476	457
		M	3.867	3.815				4.500	2.747	471.7	452.8
	B	**W**: $C=6.8194$, $K=7.3167$	6.394	6.684	0.129	0.024	0.0002			845.9	2042.9
		M	6.383	6.716				7.992	4.548	845.9	2042.9
	C	**W**: $C=8.3467$, $K=74.3606$	8.283	8.345	0.530	0.035	0.0003			1128.3	947.8
		M	8.282	8.295				8.529	8.000	1134.5	953
Amman	A	**W**: $C=3.8207$, $K=5.5697$	3.530	3.687	0.080	0.120	0.008			419.7	600.2
		M	3.536	3.518				4.959	2.098	425	607.8
	B	**W**: $C=7.2104$, $K=10.7377$	6.890	6.973	0.281	0.728	0.134			890.7	1720.8
		M	6.693	7.983				7.996	5.189	891.3	1721.9
	C	**W**: $C=8.34464$, $K=58.939$	8.267	8.344	0.130	0.227	0.013			1129	980
		M	8.262	8.023				8.596	8.023	1131.5	982.2
Rewashed	A	**W**: $C=3.9067$, $K=6.2438$	3.632	3.799	0.071	0.315	0.0590			441.8	649.4
		M	3.638	3.353				4.956	2.373	440.5	647.5
	B	**W**: $C=6.9292$, $K=9.1427$	6.566	6.842	0.137	0.299	0.0280			871	1774.6
		M	6.572	6.419				7.982	5.032	872.5	1777.7
	C	**W**: $C=8.3963$, $K=58.1826$	8.315	8.394	0.367	0.027	0.0002			1126.8	883.4
		M	8.316	8.432				8.597	8.018	1131.2	886.9
Umm-Jemal	A	**W**: $C=5.4666$, $K=3.7253$	4.935	5.027	0.057	0.029	0.0003			630.9	2162
		M	4.921	5.065				7.455	1.610	628.8	2154.9
	B	**W**: $C=8.0049$, $K=52.2106$	7.919	8.002	0.864	0.033	0.0003			1082.4	1030.4
		M	7.919	8.049				8.357	7.531	1078.7	1026.9

Moreover, the PV-generator given in [13] is considered to compute solar power and solar energy at each chosen location.

3. Results and discussion

This section presents simulations to assess the potential of renewable energy resources, namely wind and solar, at different sites in Jordan. Long-term measured data of wind speeds and solar irradiations at each considered site are utilized to find the characteristics of both wind speeds and solar irradiations. In addition, the power potential of wind and solar resources are presented.

3.1. Assessment of wind energy potential

Table 1 shows eight chosen sites which are examined to estimate wind energy potential in Jordan. The metrological wind speed data were measured using a cup anemometer on a daily basis, every 6 h. The data was collected, by the Jordanian meteorological department, from the first of January 1998 until the last day of December 2008. Profiles of monthly averaged wind speed data for three different heights (10 m, 40 m, and 60 m) are shown in Fig. 1A–H.

The results of wind speed characteristics computed by the metrological approach and the corresponding results based on the statistical Weibull distribution (WD) method are given in Table 2. The same sort of results when the height is adjusted to 40 m is given in Table 3. The symbols **M** and **W** used in the tables are stand for Metrological and Weibull, respectively. Based on the results obtained it can be noticed that:

- For most locations, summer season represents the richest period in wind speeds. The results of wind speed characteristics show that the potential of wind energy is acceptable for most of the selected locations. For example, the most energetic wind speed for most selected sites is greater than 3 m/s.
- Ras-Muneef gains the heights rank in wind energy potential followed by Aqaba and South-Azarq. The poorest site is Gur Al-Safi.
- By increasing hub's height from 10 m to 40 m, wind power is increases more than two times. The same positive effect can be seen for wind energy.
- A very close agreement between M-method results and those obtained by Webull distribution method. This confirms the accuracy and the validity of the analysis carried out in the present work.

3.2. Assessment of solar energy potential

Seven Jordanian locations are examined in the current study to evaluate solar energy potential in Jordan. These sites are shown in Table 4. At each location, daily average solar irradiation was measured, by the Jordanian Energy Research Center, and the collected data from the first of January 2004 until the thirty first of December 2008 are used in the study. Profiles of daily average solar insolation levels for the selected sites are shown in Fig. 2A–G. Fig. 3 shows Profiles of monthly averaged max and minimum solar irradiation in Umm-Jemal site.

For each location, irradiance data are separated into groups (clusters) and Weibull distribution is examined to fit each group

using graphical demonstration as well as goodness of fit tests. Histogram and probability density functions versus average daily irradiance levels of clusters A, B and C for Karak location are shown in Fig. 4A–C, respectively. The empirical and fitted distributions of these three clusters are shown in Fig. 5A–C. In each of the previous figures, meteorological data and Weibull method results are represented by solid line and dashed line, respectively. Solar irradiance data for each of the other chosen locations are tested following the same procedure. Based on the graphical demonstration and statistical test results it can be stated that Weibull method is a highly convincing choice to describe the three separated groups of the long-term measured solar irradiation levels. The graphical demonstrations for the other locations are not presented in this paper but the results of statistical tests including root mean square error (RMSE), *P*-value and Chi-square (C.S.) are given in Table 5.

The computed results of the meteorological approach and the corresponding results obtained by the statistical WD method are given in Table 5. For each cluster of a chosen site, the results of mean insolation level λ_M, most frequent irradiance λ_F, solar power and solar energy are presented.

The profiles of solar irradiance (Figs. 2A–G and 3) and the results presented in Table 5 show that Jordan has a great potential of solar energy. For most locations cluster C gains the height rank of solar irradiance characteristics followed by cluster B and lastly cluster A. Cluster C represents the period of May–August during the year. From the results given in Table 5, it can be observed that the computed results using the WD statistical method are very close to the corresponding results obtained by the meteorological approach. This confirms the accuracy and the validity of the analysis carried out in the present paper.

4. Conclusion

The potential of renewable energy resources; namely wind and solar, in Jordan has been investigated in the current paper. Wind speed characteristics and wind power potential are computed for each site using the meteorological and statistical methods. The long-period measured solar irradiance data are divided into clusters and WD-model is used to fit the data of each group. Irradiance characteristics and solar power potential are evaluated at each selected location. Based on the extensive results presented in this paper, it could be concluded that Jordan has a great potential to utilize various stand-alone or grid-connected wind/PV energy systems.

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